On the quantitative interpretation of dark energy by quantum effect of gravity and experimental scheme with atom interferometer

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Abstract

From the general principle that gravity originates from the coupling and thermal equilibrium between matter and vacuum background, we give two simple equations to calculate the quantum effect of gravity. From these two equations, we calculate the ratio between the dark energy density and that of the sum of the dark matter density and ordinary matter density. Without any fitting parameter, the ratio is calculated as 2.36, which agrees quantitatively with the result 7/3 obtained from various astronomical observations. The same quantum gravity effect explaining dark energy will also lead to abnormal gravity for a sphere full of superfluid helium. It is shown that with an atom interferometer placed in this sphere, the accuracy $\Delta g/g$ below 10^{-8} could be used to test our idea, which satisfies the present experimental technique of atom interferometer. The abnormal gravity effect would have important potential applications in black hole, possible experimental test of many-world interpretation, and even in condensed matter physics and material physics.

Although Newton's gravity law and Einstein's general relativity have given marvelous understanding about gravity, it is still the most mysterious problem in the whole field of science [1]. It is widely believed that the unification of gravity and quantum mechanics and the unification of gravity and other three fundamental forces are impossible in the foreseeable future. Recently, Verlinde's work [2] has renewed enthusiasm of the possibility that gravity is an entropy force, rather than a fundamental force [3]. Of course, if gravity is not a fundamental force, the unification problem does not exist any more. However, we can claim a solution of the unification problem, only when new observable effect is verified experimentally and new view of gravity can solve unresolved problems in a simple and ingenious way.

In this work, we consider the quantum effect of gravity based on the general principle that gravity originates from the coupling and thermal equilibrium between matter and vacuum background. For classical particles, this general principle gives the Newton's gravity law. For particles described by quantum wave packets, it leads an abnormal quantum effect of gravity [4]. It is shown unavoidably that the dark energy is a natural result of the coupling and thermal equilibrium between matter and vacuum background. We calculate the ratio between the dark energy density and that of the sum of the dark matter density and ordinary matter density. Without any fitting parameter, the ratio is 2.36 with very simple derivations, which agrees quantitatively with the result 7/3 obtained from various astronomical observations. Our works also show that, with a sphere full of superfluid helium, there is a feasible experimental scheme to test our idea with an atom interferometer placed in the sphere. The accuracy $\Delta g/g$ below 10^{-8} could be used to test our idea, which satisfies the present experimental technique of atom interferometer [5]. If it is verified, the abnormal gravity effect would have important potential applications in black hole, possible experimental test of many-world interpretation, and even in condensed matter physics, material physics, *etc.*

The pioneering works by Jacobson [3] and Verlinde [2] have suggested a new understanding about the origin of Newton's gravity. These advances were motivated by the fact that the gravity law closely resembles the laws of thermodynamics and hydrodynamics [6–11]. In our previous work [12], without the introduction of the concept of holographic screen in Verlinde's work [2], we give a simple derivation of Newton's gravity law and Unruh effect. In Einstein's theory, it is assumed that the spacetime is curved by the presence of an object,

which results in the gravity for another object. In the new view of gravity, for an object with mass M, it establishes a temperature field of $T(\mathbf{R}) \sim M/|\mathbf{R}|^2$. Using the Unruh formula $|\mathbf{a}| = 2\pi k_B cT/\hbar$ about the relation between acceleration and temperature, it is easy to get the Newton's gravity law $F = GMm/R^2$ between two classical objects.

The quantum effect of gravity has been studied in our previous work [4]. Here we give a brief introduction to this quantum gravity effect. Assuming there are N particles whose wave functions are $\phi_1(\mathbf{x},t), \cdots, \phi_j(\mathbf{x},t), \cdots, \phi_N(\mathbf{x},t)$, we give here the formulas to calculate the acceleration field for a classical particle due to these N particles. As shown in previous works by Verlinde *et al.* [2, 4, 12], the acceleration field for this classical particle physically originates from the temperature field distribution $T(\mathbf{R})$ which is established by the coupling between these N particles and the vacuum background. From the Unruh temperature [10], we have $|\mathbf{a}| = 2\pi k_B cT/\hbar$. However, the acceleration is a vector, while T is a scalar field larger than zero. The most simple way to get the acceleration field is

$$\mathbf{a}(\mathbf{R}) = \frac{2\pi k_B c}{\hbar} \sum_{j=1}^{N} T_j(\mathbf{R}) \frac{\nabla_{\mathbf{R}} T_j(\mathbf{R})}{|\nabla_{\mathbf{R}} T_j(\mathbf{R})|}. \tag{1}$$

Here $T_j(\mathbf{R})$ is the temperature field distribution due to the jth particle, $\hbar$ the reduced Planck constant, k_B the Boltzmann constant, and c the light velocity. It is clear that the direction of this acceleration has the tendency of making the particle increase its temperature, which agrees with the tendency of thermal equilibrium to decrease the free energy $F_{fe} = U - TS$. Together with Eq. (2), this explains why the gravity between two classical particles is attractive. In this paper, note that all bold symbols represent vectors.

We assume further that $T_j(\mathbf{R})$ takes the following form

$$T_j(\mathbf{R}) = \frac{\hbar G m_j}{2\pi k_B c} \left| \int d^3\mathbf{x} \phi_j^*(\mathbf{x},t) \frac{\mathbf{x} - \mathbf{R}}{|\mathbf{x} - \mathbf{R}|^3} \phi_j(\mathbf{x},t) \right|. \tag{2}$$

Here m_j is the mass of the jth particle, G the gravitational constant. The integral in the left-hand side of Eq. (2) is due to the quantum wave packet of the jth particle, while the norm of the vector after calculating this integral is due to the fact that T_j is a scalar field larger than zero and T_j is an observable quantity based on Eq. (1). It is easy to show that if all these N particles are highly localized classical particles, we get the Newton's gravity law $\mathbf{a}(\mathbf{R}) = -\sum_j Gm_j(\mathbf{R} - \mathbf{x}_j)/|\mathbf{x}_j - \mathbf{R}|^3$, with $\mathbf{x}_j$ being the location of the jth particle.

Now we turn to consider a quantum sphere with radius R_s shown in Fig. 1. We consider the situation that $|\phi_j(\mathbf{x},t)| = 1/\sqrt{4\pi R_s^3/3}$ within the quantum sphere and $|\phi_j(\mathbf{x},t)| = 0$

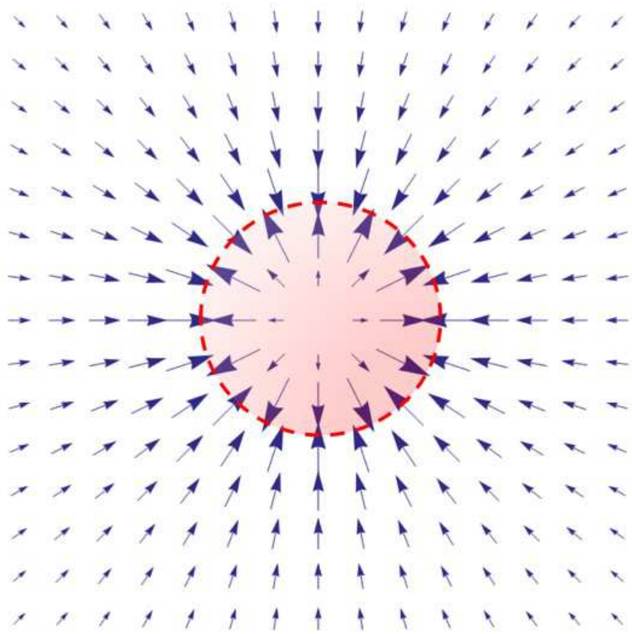

FIG. 1: Quantum gravity effect of a quantum sphere comprising particles with delocalized wave packets in the whole quantum sphere. The dashed circle gives the boundary of a three-dimensional quantum sphere, while the acceleration field is shown by blue arrows.

outside the quantum sphere. From Eqs. (1) and (2), the acceleration fields for a classical particle within and outside the quantum sphere are

$$\begin{aligned}\mathbf{a}\left(\mathbf{R}\right) &= \frac{4\pi}{3}Gn\mathbf{R}, R=\left|\mathbf{R}\right|<R_s, \\ \mathbf{a}\left(\mathbf{R}\right) &= -\frac{G\Sigma_j m_j}{R^3}\mathbf{R}, R=\left|\mathbf{R}\right|>R_s. \end{aligned} \tag{3}$$

Here $n=N/\sqrt{4\pi R_s^3/3}$ is the average density of the quantum sphere. We see an abnormal gravity effect in the interior of the quantum sphere, where the quantum gravity effect is repulsive. We will show in due course that this abnormal gravity effect leads to a dark energy density agreeing quantitatively with the astronomical observations. As for the noncontinuous distribution of the acceleration field at the boundary of the quantum sphere, Ref. [4] gives several discussions and in particular its potential application to black hole.

As shown above, the presence of various matters will establish a temperature field due to the coupling with the vacuum background. Obviously, there is a finite temperature distribution in the vacuum background too. This finite temperature characteristic of the vacuum background originates from various excitations from the vacuum. From a reference

system in the vacuum background, we define the space coordinate as $\mathbf{R}$. If the big bang of the origin of our universe is adopted (see Fig. 2), the velocity distribution in this reference system of the vacuum background is $v(R) = Rc/R_u$, based on Hubble's law. Here $R_u = ct_u$ with t_u being the age of the universe. The energy density of the matter in this reference system is then

$$\varepsilon_m^2(R) = n_m^2 c^4 + \frac{n_m^2 c^4 R^2/R_u^2}{1 - R^2/R_u^2}. \tag{4}$$

When the coupling and local thermal equilibrium between matter and vacuum background are considered, we have

$$\varepsilon_m \Delta V = \frac{1}{2} k_B T_m = \frac{1}{2} k_B T_v = n_v \Delta V c^2. \tag{5}$$

In Refs. [2, 12], it is suggested that the volume $\Delta V \sim l_p^3$ with $l_p = \sqrt{\hbar G/c^3}$ being the Planck length. T_m is the temperature field distribution due to the dark matter and ordinary matter. The introduction of T_v for the vacuum background is due to the coupling and thermal equilibrium between matter and vacuum background. Therefore, n_v is the density distribution of the excitations from the vacuum background due to the presence of matter. In this situation, we have

$$n_v(R) = n_m \sqrt{1 + \frac{R^2/R_u^2}{1 - R^2/R_u^2}}. \tag{6}$$

Note that this spatially dependent vacuum density distribution originates from the choice of reference. The Hubble's law has shown that, at other locations of our universe, we will get the same vacuum density distribution (6). Hence, the meaningful vacuum density is the averaged density as follows

$$\overline{n}_v = \frac{4\pi \int_0^{R_u} n_v R^2 dR}{V_u}. \tag{7}$$

Here $V_u = 4\pi R_u^3/3$. In this situation, we get

$$\frac{\overline{n}_v}{n_m} = 3 \int_0^1 y^2 \sqrt{1 + \frac{y^2}{1 - y^2}} dy \approx 2.356. \tag{8}$$

We see that this ratio does not directly depend on l_p and R_u. Therefore, it is a universal value based on the big bang origin of our universe and the validity of the Hubble's law.

Considering the fact that various fields in the vacuum have the propagation velocity of c (see detailed discussions in Ref. [4]), it is not unreasonable to assume that various fields in the vacuum background have delocalized wave packets in the whole universe. Another reason

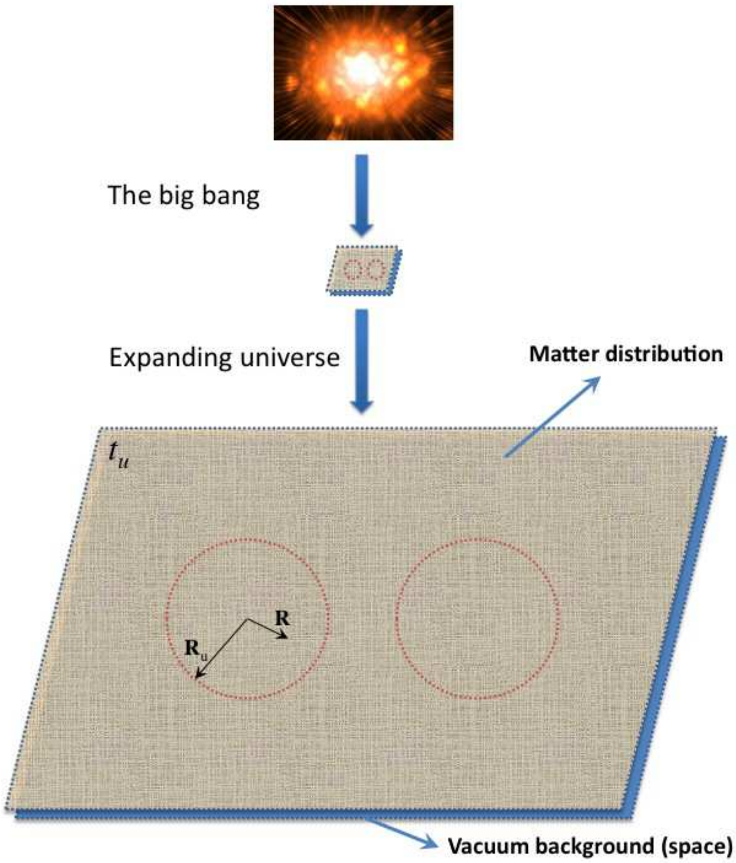

FIG. 2: The big bang origin of our universe. There is a strong coupling between matter and vacuum, so that there is a local thermal equilibrium, which leads to various excitations from the vacuum. These excitations in the vacuum lead to an accelerating expansion of the universe, which is just the effect of so-called dark energy.

is that $R_u = ct_u$ (t_u is the age of the universe), so that this age could lead to delocalized wave packets at least within the region $|\mathbf{R}| < R_u$. The third reason is that when the coupling between matter and vacuum is considered, the vacuum has the characteristic of superfluidity (see detailed discussions in Ref. [4]). With this assumption, from Eqs. (1), (2) and (3), for $R < R_u$, the acceleration field for a classical particle is

$$\mathbf{a}_v(\mathbf{R}) = \frac{4\pi}{3} G\overline{n}_v \mathbf{R}. \tag{9}$$

As shown from Eqs. (1) and (2), once the delocalized wave function in the whole universe is satisfied, the above equation always holds, regardless of the specific composition in the vacuum background. From this equation, we see that the vacuum background has an effect of accelerating the expansion of our universe. The linear relation between $\mathbf{a}_v$ and $\mathbf{R}$ means that

different reference systems at different locations in our universe will has the same law given by Eq. (9). With analytical continuation, for the civilized world in the region $|\mathbf{R}| > R_u$, Eq. (9) can still be used in their reference system.

The presence of dark matter and ordinary matter will have an effect of decelerating the expansion of our universe, which is given by

$$\mathbf{a}_m(\mathbf{R}) = -\frac{4\pi}{3} G n_m \alpha \mathbf{R}. \tag{10}$$

Here α is a coefficient when the relativistic effect is considered. In the nonrelativistic approximation, $\alpha = 1$. With the assumption of flat universe, our calculations show that there is no significant relativistic correction for $R < 0.8R_u$.

From the nonrelativistic approximation, the ratio $\overline{n}_v/n_m$ directly corresponds to the result of astronomical observations. In astronomical observations, n_m is measured with various means when gravity effect is considered. Almost all astronomical observations show that the ratio $\overline{n}_v/n_m$ is about 7/3 [13–17]. From our theoretical result of 2.356 given by Eq. (8), we see amazing agreement with this observation result.

Note that the validity of the above simple derivations is due to the fact that our universe is flat. It is quite interesting to note that from the measured dark matter density and ordinary matter density, the ratio given by Eq. (8) just satisfies the request of flat universe based on the Friedmann-Lemaître cosmological model. This consistency indirectly supports the statement that there should be significant proportion of dark matter.

Most quantum field theories predict a huge value for the quantum vacuum. It is generally agreed that this huge value should be decreased 10^{-120} times to satisfy the observation result. Because there are no "true" wave functions for these "quantum zero-point states", based on our theory, even there are huge vacuum energy due to "quantum zero-point states", the gravity effect should be multiplied by zero! Another reason is that, the assembly of quantum zero-point states itself does not mean a nonzero temperature field. The finite temperature characteristic of the vacuum is due to the excitations from the vacuum, which influence the motion of the matters. Based on our theory, the cosmological constant problem is not a "true" problem at all.

In this work, the vacuum energy calculated by us is due to the coupling and local thermal equilibrium between matter and vacuum background. The coupling and local thermal equilibrium lead to various "true" excitations from the vacuum. What we calculated in

this work is in fact aimed at these excitations which can be described by sophisticated and delocalized wave functions.

Now we turn to consider a feasible experimental scheme to test further the quantum gravity effect with superfluid ^{4}He, shown in Fig. 3. For brevity's sake, we consider a sphere full of superfluid ^{4}He. There is a hole in this sphere. In this situation, from Eqs. (1) and (2), the gravity acceleration in the sphere due to superfluid ^{4}He can be approximated as

$$\mathbf{a} = \frac{4\pi}{3} G n_{He} \mathbf{R}. \tag{11}$$

Here the liquid helium density is $n_{He} \approx 550$ kg/m^3. From this, the anomalous acceleration is $\mathbf{a} = 1.5 \times 10^{-7} \mathbf{R}$. The gradient of this anomalous acceleration is $1.5 \times 10^{-7}/s^2$. Even only the condensate component of superfluid ^{4}He is considered, this anomalous acceleration can be larger than $10^{-8} R$. Quite interesting, this value is well within the present experimental technique of atom interferometer [5] to measure the gravity acceleration. Nevertheless, this is a very weak observable effect. Thus, it is unlikely to find an evidence to verify or falsify this anomalous acceleration without future experiments.

Because highly localized helium atoms will not lead to quantum effect of gravity, the measurement of acceleration will give us new chance to measure the fraction of highly localized helium atoms, which is still an important and challenging topic in condensed matter physics. In our theory, the quantum effect of gravity does not rely on superfluid behavior. It depends on whether the wave packet of a particle is localized. It is well known that whether there is wave packet localization is a central topic in condensed matter physics and material physics, such as the long-range order problem at a phase transition. Considering the remarkable advances in atom interferometer [5], it is promising that the quantum gravity effect would have potential applications in our understanding of condensed matter physics and material physics, *etc.*

The potential application of the quantum gravity effect for black hole has been studied in Ref. [4]. Here, we argue that it even could give a possible experimental scheme to test many-world interpretation [18]. In many-world interpretation, there is no "true" wave packet collapse process. For a particle described by a wave packet, the measurement result of the particle at a location does not mean that the wave packet of this particle at other locations disappears. It suggests that the wave function of the whole universe evolves into a series of orthogonal many-body wave functions due to the interaction between the measurement

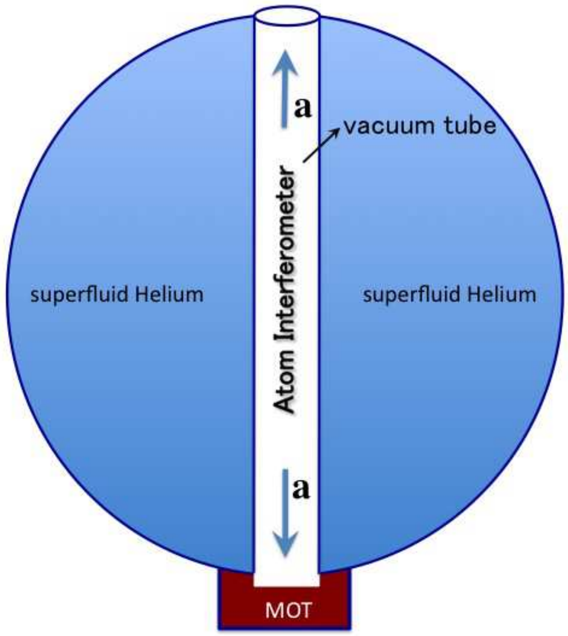

FIG. 3: An experimental scheme to test the abnormal quantum gravity effect. In the hole of the superfluid helium sphere, various apparatuses measuring the gravity acceleration are placed in a vacuum tube, while the magneto-optical trap (abbreviated MOT) of cooling and trapping cold atoms may be placed outside the sphere.

apparatus and the particle. The observed result of the particle at a location corresponds to one of the orthogonal many-body wave functions. Considering again the superfluid helium sphere, if we increase the temperature so that it becomes normal liquid, based on the many-world interpretation, the wave packets of helium atoms (at least the fraction of the helium atoms initially in the condensate) are still localized in the whole sphere. In this situation, if the many-world interpretation is correct, it is possible that one may also get the abnormal quantum gravity effect. This would mean a gravity effect dependent on the history of an object. At least, it seems that all previous experiments or astronomical observations do not overrule this possibility. The present work clearly shows that it's time to consider more seriously the new view of gravity, in particularly by future experiments.

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[1] S. Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity* (New York, Wiley-VCH, 1972).

[2] E. Verlinde, arXiv: 1001.0785 (2010).

[3] T. Jacobson, Phys. Rev. Lett. **75**, 1260 (1995).

[4] H. W. Xiong, arXiv:1101.0525 (2010).

[5] Alexander D. Cronin, Joerg Schmiedmayer, David E. Pritchard, Rev. Mod. Phys. **81**, 1051 (2009).

[6] J. D. Bekenstein, Phys. Rev. D **7**, 2333 (1973).

[7] J. M. Bardeen, B. Carter, and S. W. Hawking, Commun. Math. Phys. **31**, 161 (1973).

[8] S. W. Hawking, Commun Math. Phys. **43**, 199 (1975).

[9] P. C. W. Davies, J. Phys. A **8**, 609 (1975).

[10] W. G. Unruh, Phys. Rev. D **14**, 870 (1976).

[11] T. Padmanabhan, Rep. Prog. Phys. **73**, 046901 (2010).

[12] H. W. Xiong, arXiv:1012.5858 (2010).

[13] Adam G. Riess *et al.*, Astronomical J. **116**, 1009 (1998).

[14] S. Perlmutter *et al.*, Astrophysical J. **517**, 565 (1999).

[15] http://lambda.gsfc.nasa.gov/product/map/current/map_bibliography.cfm

[16] M. Kowalski *et al.*, Astrophys. J. **686**, 749 (2008).

[17] http://lambda.gsfc.nasa.gov/product/map/dr4/pub_papers/sevenyear/basic_results/wmap_7yr_basic_results.pdf.

[18] H. Everett, Rev. Mod. Phys. **29**, 454 (1957).